AFRL-AFOSR-UK-TR-2012-0008

A Proposal to Initiate Regional Studies of Ionospheric Irregularities in the African Region

Sandro M. Radicella

Abdus Salam International Centre for Theoretical Physics
Aeronomy and Radiopropagation Laboratory
Strada Costiera, 11
Trieste, Italy 34014

EOARD GRANT 09-3099

Report Date: March 2012

Final Report for 28 August 2009 to 28 September 2011

Distribution Statement A: Approved for public release distribution is unlimited.

Air Force Research Laboratory
Air Force Office of Scientific Research
European Office of Aerospace Research and Development
Unit 4515 Box 14, APO AE 09421

REPORT DOCUMENTATION PAGE	Form Approved OMB No. 0704-0188

1. REPORT DATE ***(DD-MM-YYYY)***	**2. REPORT TYPE**	**3. DATES COVERED** *(From – To)*
29-03-2012	Final Report	28 August 2009 – 28 September 2011

4. TITLE AND SUBTITLE

A Proposal to Initiate Regional Studies of Ionospheric Irregularities in the African Region

5a. CONTRACT NUMBER

FA8655-09-1-3099

5b. GRANT NUMBER

Grant 09-3099

5c. PROGRAM ELEMENT NUMBER

61102F

6. AUTHOR(S)

Professor Sandro M. Radicella

5d. PROJECT NUMBER

5d. TASK NUMBER

5e. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

Abdus Salam International Centre for Theoretical Physics
Aeronomy and Radiopropagatio Laboratory
Strada Costiera, 11
Trieste, Italy 34014

8. PERFORMING ORGANIZATION REPORT NUMBER

N/A

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

EOARD
Unit 4515 BOX 14
APO AE 09421

10. SPONSOR/MONITOR'S ACRONYM(S)

AFRL/AFOSR/RSW (EOARD)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

AFRL-AFOSR-UK-TR-2012-0008

12. DISTRIBUTION/AVAILABILITY STATEMENT

Approved for public release; distribution is unlimited.

13. SUPPLEMENTARY NOTES

14. ABSTRACT

It is well known that unique world-wide studies of ionospheric behavior have been made possible with GPS dual-frequency receivers that are designed to measure total electron content and to detect ionospheric irregularities. Unfortunately, the ionosphere over Africa has remained a mystery due to the sparse distribution of ionospheric sensors over this vast continent. Particularly, satellite observations have shown significant differences in the morphology of ionospheric irregularities over the low latitude regions at different longitudes (Gentile, et al., 2006).
ICTP and Boston College (BC) through respectively the Aeronomy and Radiopropagation Laboratory (ARPL) and the Institute for Scientific Research have established a partnership to promote research activities in the field of GNSS science and technology and specifically ionospheric research in Africa. Through the partnership a series of training workshops have been carried out in Trieste and African institutions contributing substantially to the establishment of a knowledgeable workforce in the continent. This Grant has allowed us to strengthen the ICTP-BC partnership and promote joint research and capacity building in the continent. In fact, the major objective of this project is to initiate studies that will fill in the fundamental gaps of information on the ionosphere behavior over the African region. As result of the work supported also by the EOARD grant, ionospheric studies in several African Universities have started involving local professors and Master and PhD students. Studies have been carried out comparing ionospheric irregularities characteristics in Africa and in South America. Other research efforts have been dedicated to the characterization of the total electron density variability over Africa and to the ionospheric electron density specification at subregional scale in the African continent by GPS total electron content data ingestion in an ionospheric electron density model.
An additional objective of the project was to install up to four receivers in locations in Africa were university research groups have been initiated. Because of the increase of costs only three receivers were brought. The acquired instruments had to be modified at BC to enable automatic transmission of the data to ICTP and BC. However prior to sending the receivers to ICTP, BC had to input the software that processes the data and enables the data to be automatically returned for further analysis. After the software upload, each receiver and antenna pair were set up for testing at BC. During this task, it was found that the antennas indicated the presence of unrealistic noise and multipath. After several discussions with the manufacturer, the original antennas were returned and replaced with new antennas. With the new antennas, the systems were rechecked. Two of the four new antennas failed once again. The faulty antennas were replaced and a final test of the systems was successful. Only now the receivers are ready to be sent to ICTP and proceed to deploy them in Africa. For this reason the scientific research reported in this document has been done with data obtained with receivers already installed in African locations as a preliminary work that will be enlarged when data from the receivers to be installed will become available.

15. SUBJECT TERMS

EOARD, Space Weather, Ionosphere

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18, NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON**
a. REPORT	**b. ABSTRACT**	**c. THIS PAGE**			SCOTT DUDLEY, Lt Col, USAF
UNCLAS	UNCLAS	UNCLAS	SAR	14	**19b. TELEPHONE NUMBER** *(Include area code)* +44 (0)1895 616162

Report of the activities done in the framework of the EOARD Grant Grant FA8655-09-1-3099

(Sep 2009- September 2011)

S. M. Radicella

The Abdus Salam International Centre for theoretical Physics (ICTP) Trieste, Italy

INTRODUCTION

It is well known that unique world-wide studies of ionospheric behavior have been made possible with GPS dual-frequency receivers that are designed to measure total electron content and to detect ionospheric irregularities. Unfortunately, the ionosphere over Africa has remained a mystery due to the sparse distribution of ionospheric sensors over this vast continent. Particularly, satellite observations have shown significant differences in the morphology of ionospheric irregularities over the low latitude regions at different longitudes (Gentile, et al., 2006).

ICTP and Boston College (BC) through respectively the Aeronomy and Radiopropagation Laboratory (ARPL) and the Institute for Scientific Research have established a partnership to promote research activities in the field of GNSS science and technology and specifically ionospheric research in Africa. Through the partnership a series of training workshops have been carried out in Trieste and African institutions contributing substantially to the establishment of a knowledgeable workforce in the continent. The EOARD Grant FA8655-09-3099 has allowed to strengthen the ICTP-BC partnership and promote joint research and capacity building in the continent. In fact, the major objective of this project is to initiate studies that will fill in the fundamental gaps of information on the ionosphere behaviour over the African region. As result of the work supported also by the EOARD grant, ionospheric studies in several African Universities have started involving local professors and Master and PhD students. Studies have been carried out comparing ionospheric irregularities characteristics in Africa and in South America. Other research efforts have been dedicated to the characterization of the total electron density variability over Africa and to the ionospheric electron density specification at subregional scale in the African continent by GPS total electron content data ingestion in an ionospheric electron density model.

An additional objective of the project was to install up to four receivers in locations in Africa were university research groups have been initiated. Because of the increase of costs only three receivers were brought. The acquired instruments had to be modify at BC to enable automatic transmission of the data to ICTP and BC. However prior to sending the receivers to ICTP, BC had to input the software that processes the data and enables the data to be automatically returned for further analysis. After the software upload, each receiver and antenna pair were set up for testing at BC. During this task, it was found that the antennas indicated the presence of unrealistic noise and multipath. After several discussions with the manufacturer, the original antennas were returned and replaced with new antennas. With the new antennas, the systems were rechecked. Two of the four new antennas failed once again. The faulty antennas were replaced and a final test of the systems was successful. Only now the receivers

are ready to be sent to ICTP and proceed to deploy them in Africa. For this reason the scientific research reported in this document has been done with data obtained with receivers already installed in African locations as a preliminary work that will be enlarged when data from the receivers to be installed will become available.

TRAINING ACTIVITIES

A series of joint ICTP-BC sponsored training activities has been carried out in Trieste and in Africa during the period covered by the grant:

Nigerian National Meeting on GNSS Science and Applications, Abuja, Nigeria, 16-19 November 2009.
The Workshop, co-sponsored by ICTP and BC with local organization, had the objective of promoting the establishment of a national effort towards the creation of a network of research groups in satellite navigation related activities in Nigeria. (45 participants)

Second Workshop on Satellite Navigation Science and Technology for Africa, 6-24 April 2010, Trieste.
The purposes of this workshop, co-sponsored mainly by ICTP and BC, was to increase the global navigation satellite science and applications expertise in Africa and to further develop science collaborations with the universities in the continent by promoting the establishment of research groups interested in the field. For this reason professors or senior lecturers from African universities were invited to attend together with junior scientists nominated by them. (58 participants)

Workshop on Ionosphere and its Effects on GNSS Systems, Cairo/Alexandria, Egypt10-13 January 2010
This meeting was co-organized by ICTP with participation of BC as a follow-up of the Workshop organized in Trieste to promote the establishment of a national effort towards the creation of research groups in satellite navigation related activities in Egypt.
(40 participants)

East, Central and Southern African GNSS and Space Weather Workshop, Nairobi, Kenya, 19-23 July 2010
This meeting was co-sponsored by ICTP with participation of BC as a follow-up of the Workshop organized in Trieste to promote the establishment of a network of research groups in satellite navigation related activities in Africa. (45 participants)

DIRECT EFFECTS OF THE TRAINING ACTIVITIES

As result of the training efforts done, a series of Universities in Africa have initiated research groups in the field of ionospheric science and applications. Several of them have at the present Master and PhD students with research thesis in the field. S.M.

Radicella from the ICTP has been appointed as co-supervisor of some of these thesis works. They are:

O. S. Bolaji, University of Ilorin, Ilorin, Nigeria; PhD research thesis on "Variability of total electron content and magnetic field intensity at Ilorin"

Melessew Negussie, Bahir Dar University, Bahir Dar, Ethiopia; PhD research thesis on "Three-dimensional electron density reconstruction from GPS receiver data assisted by NeQuick model for Ethiopian region ionosphere"

J. A. Owalu, Mbarara University of Science and Technology, Mbarara, Uganda; PhD research thesis on "The geomagnetic storm effects on the total electron content over Mbarara"

G. Ochieng Ondede, Maseno University, Maseno, Kenya; Master of Science research thesis on "Characterization of day-to-day variability of Total Electron Content (TEC) over Malindi as a function of time of the day"

P. Mungufeni, Mbarara University of Science and Technology, Mbarara, Uganda; Master of Science research Thesis on "Characterization of the rate of change of the total electron content over Mbarara"

RESEARCH EFFORTS

The LISN network is the first distributed observatory of ionospheric sensors covering a large land mass (Valladares and Doherty, 2009). The network was designed to establish a multiple sensors network across South America to provide a nowcast of the low-latitude ionosphere and atmosphere and to develop forecasting capabilities concerning the onset of equatorial spread-F. To achieve high quality nowcasts and forecasts, the LISN system was designed to include 50 GPS receivers, 5 magnetometers and 5 modern ionosondes able to measure also the nighttime E region and Es layers. The ionosondes and their collocated magnetometers are planned to be equally spaced from north to south on the same magnetic meridian crossing the magnetic equator at 70° W. The experimental network includes the use of small sub-arrays of GPS receivers, spaced by 4-5 km, to identify and characterize low latitude atmospheric gravity waves (AGWs) and traveling ionospheric disturbances (TIDs) and to assess experimentally their role on seeding plasma bubbles. Other tasks to be carried out under the LISN effort consists of using precise measurements of E and Es layers to investigate the role of these layers on bubble onset and dynamics and to examine the role of alternative mechanisms on plasma bubble formation. Electron density bubbles are responsible for the presence of deplitions observed in GPS derived TEC data as a funtion of time in individual satellite arcs.

One of the scientific objectives of the project supported by the EORAD grant is to compare results obtained with the LISN network in South America with those that can result from observations of the ionosphere over Africa. Differences in the behaviour of both the bachground ionospheric total electron content and irregularities (scintillations and TEC deplitions) between South America and Africa can be expected due to the distinct relation between the geographic and the geomagnetic equator in the two regions.

Due to the impossibility to deploy new receivers in Africa up to the time of this report for the reasons indicated above, data from previously installed receivers by BC were comopared with results from LISN stations placed at similar magnetic latitudes. Stations used for the analysis are indicated in Table 1.

Table 1: Stations used for comparison between South America and Africa

Station	Gegraphic Latitude	Geographic Longitude	Magnetic Latitude
Ilorin, Nigeria	8.48º	4.67º	-1.82º
Lagos, Nigeria	6.52º	3.40º	-3.2º
Cuzco, Perú	-13.52º	288.04	-1.4º
Alta Foresta, Brazil	-9.87º	303.9	-2.6º

Figure 1 shows the ionospheric scintillation index S4 for the year 2008 that corresponds to the four stations. It has to be noted that the year 2008 was one with very low solar activity as given in Table 2.

Table 2: Monthly mean sunspot number for the year 2008

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Mean R	3.3	2.1	9.3	2.9	3.2	3.4	0.8	0.5	1.1	2.9	4.1	0.8

In general only weak scintillation (low level of S4) are observed in the four stations along all the year and a clear difference cannot be defined between the values observed over Africa and those that correspond to South America. However comparison between Figures 2, 3 and 4 could be an indication that the African stations tend to measure larger values of both scintillations magnitude and depth of TEC depletions. To better define any possible difference between the ionospheric irregularities observed over South America and Africa it will be necessary to wait for years of higher solar activity. Figure 5 shows the S4 scintillation index observed in 4 days of September 2011 at Nairobi, Kenya, (Geog. Lat. 1.28^o, Geog. Lon. 36.81^o). The presence of strong scintillations with values of S4 reaching 1 are seen in the figure.

CHARACTERIZATION OF THE BACKGROUND IONOSPHERE OVER LOW LATITUDES IN AFRICA

A series of studies have been initiated to characterize the background ionosphere and its variability over the low latitudes in Africa making use of the available GPS derived TEC data. The research thesis works indicated above are oriented towards the fulfillment of such objective.

In particular the work done with O.S. Bolaji, PhD student at the University of Ilorin, Ilorin, Nigeria, and his professor J.O. Adeniyi characterize the time variability of vertical TEC in a year of low solar activity (2009) over Ilorin (Geog. Lat. 8.47^o, Geog. Lon. 4.68^o). This location lies in the region of the equatorial trough of the so called "equatorial anomaly" of the ionosphere, a region still poorly studied in the African continent. The work is described in a paper that has been sent for publication to Radio Science and at the moment is under minor revisions at request of the editors ("Variability of total electron content over an equatorial West-African station during

low solar activity” by Bolaji, O. S., Adeniyi, J. O., Radicella, S. M., and Doherty, P. H).

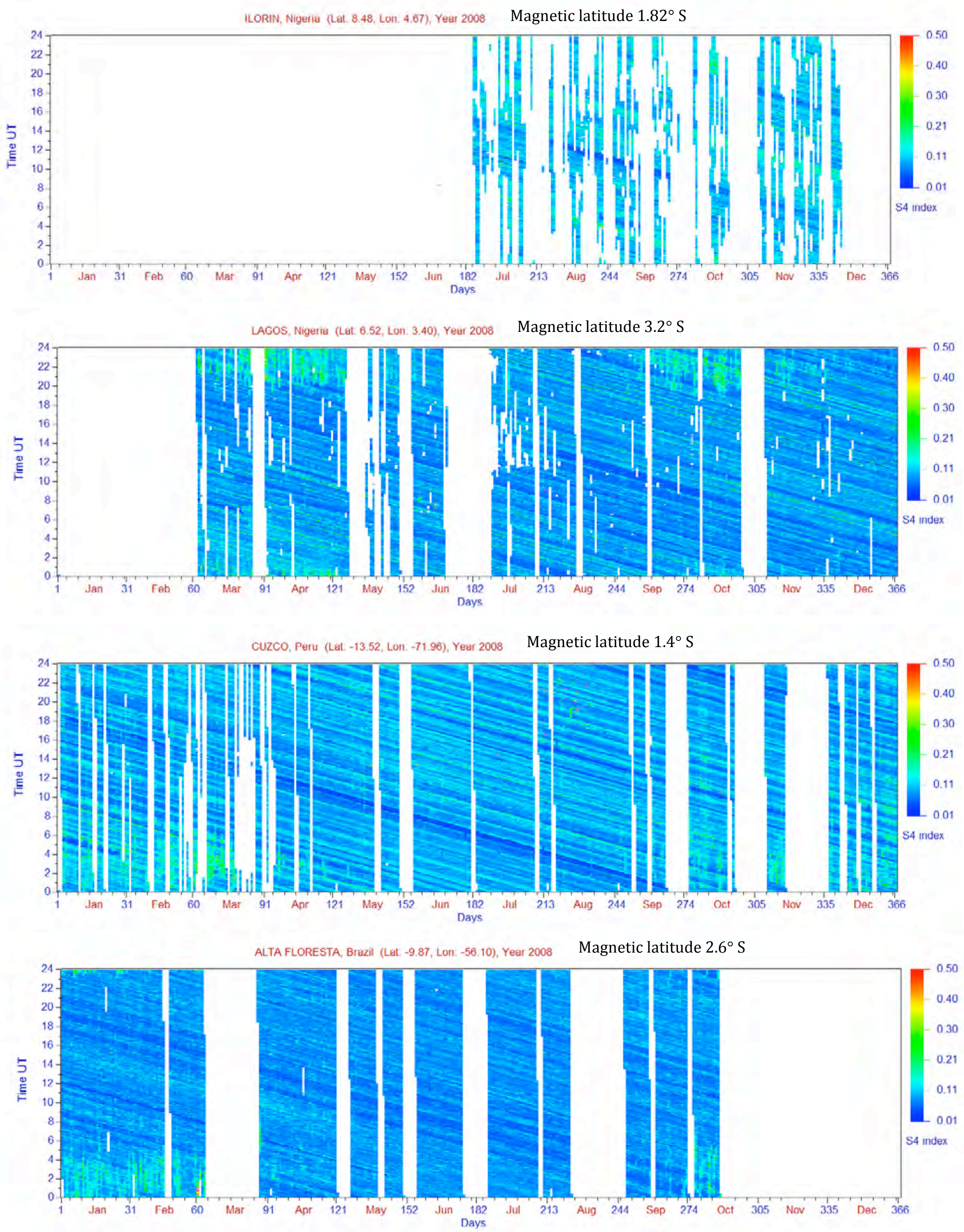
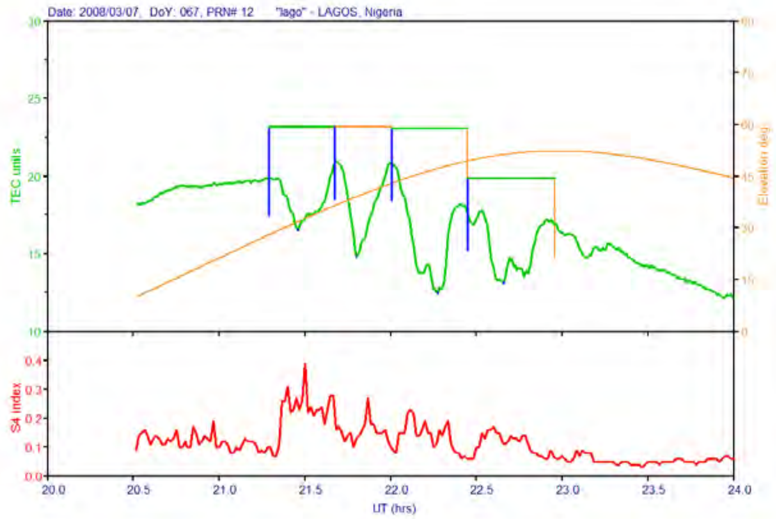
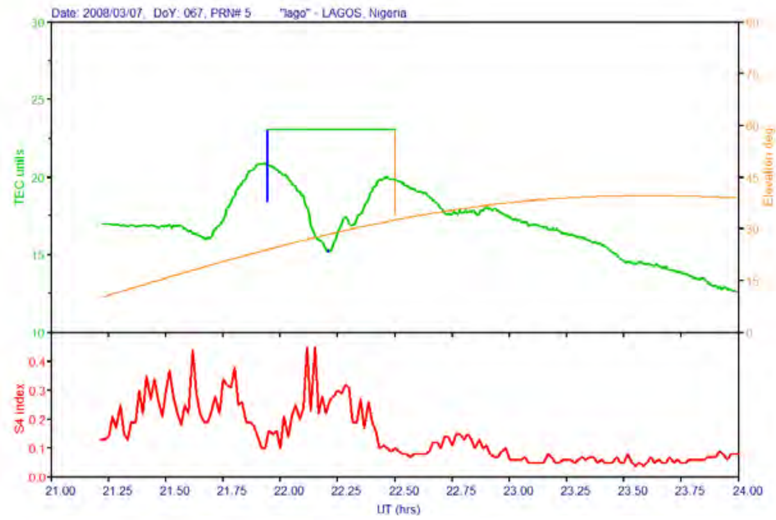


Figure 1. Scintillation (S4 index) for the year 2008 at stations Ilorin and Lagos Nigeria and at similar magnet latitude stations Cuzco, Peru and Alta Floresta Brazil





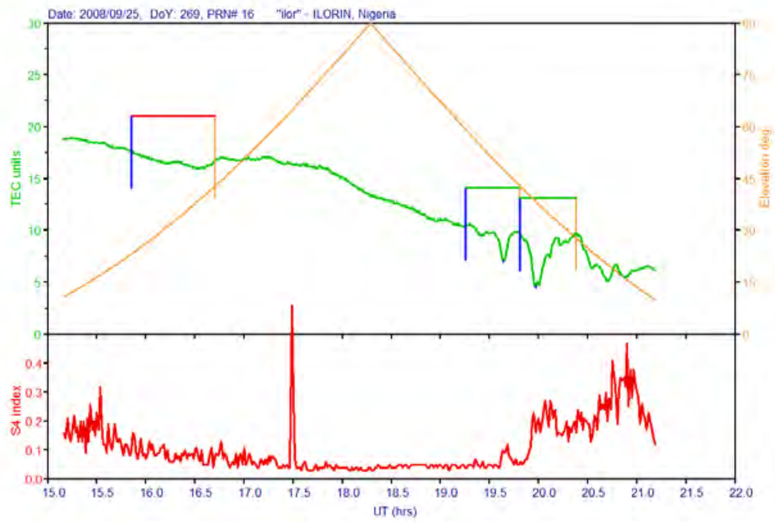


Figure 2. TEC and scintillations (S4 index) measurements with Depletions identified at stations Ilorin and Lagos Nigeria

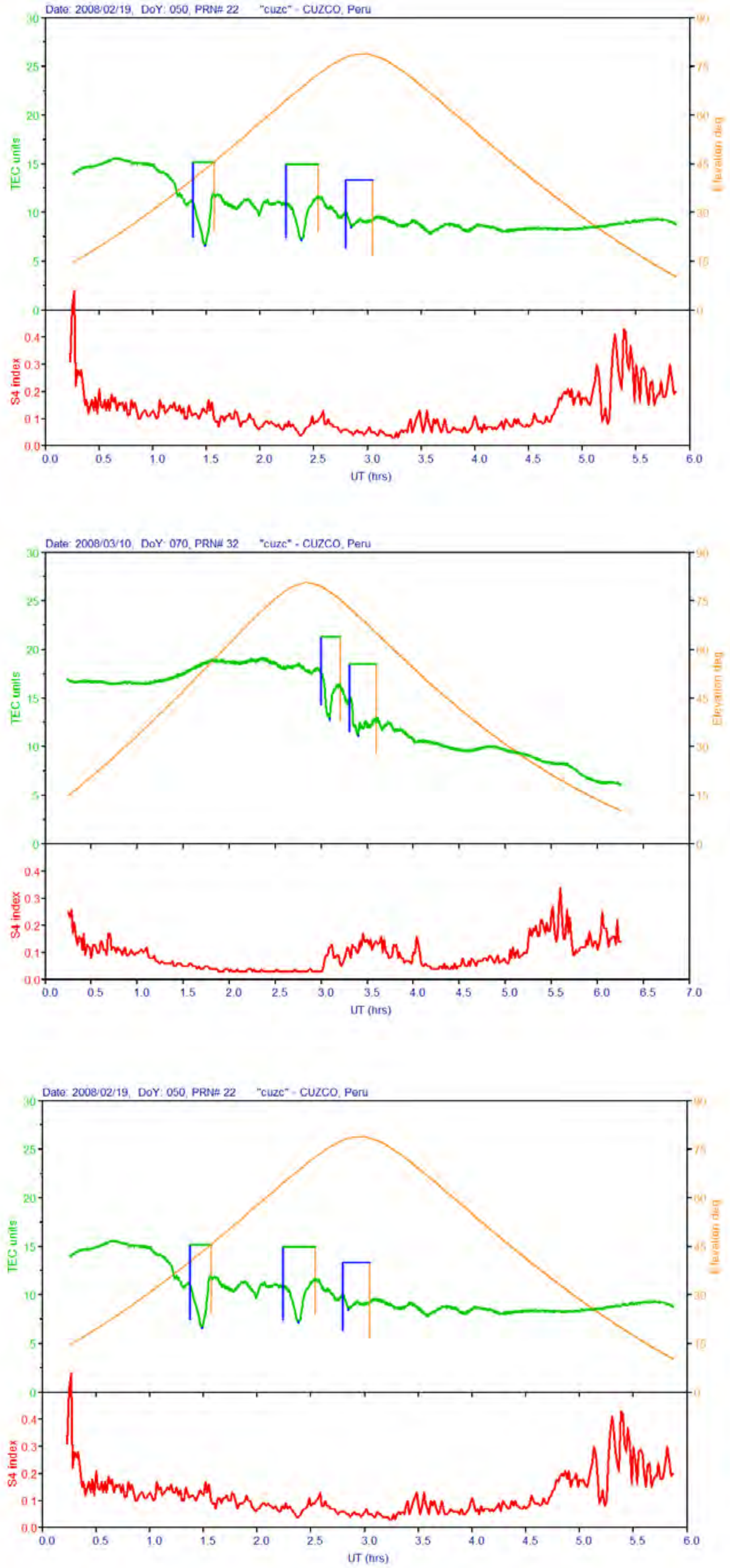


Figure 3. TEC and scintillations (S4 index) measurements with Depletions identified at station Cuzco, Peru.

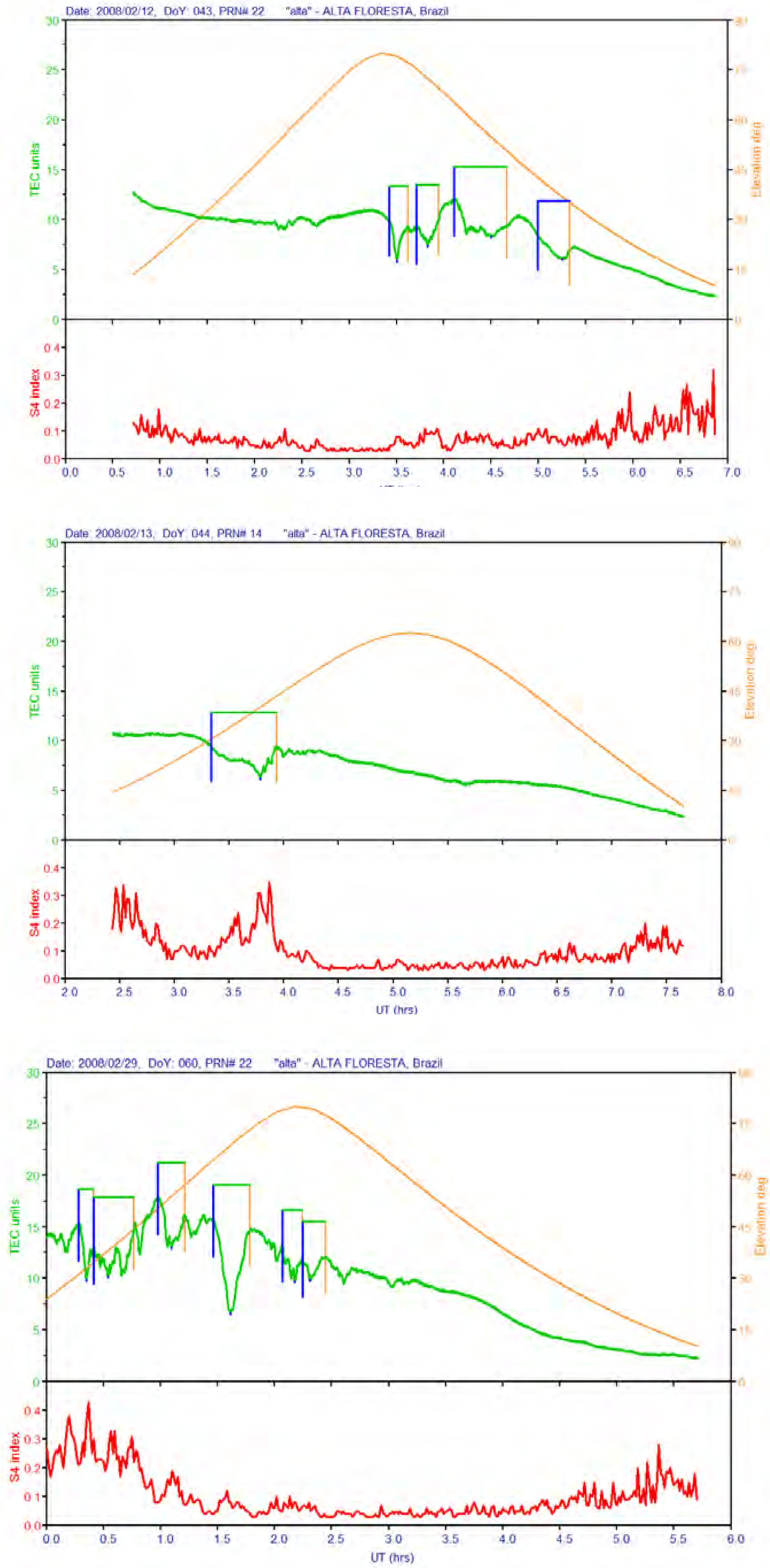
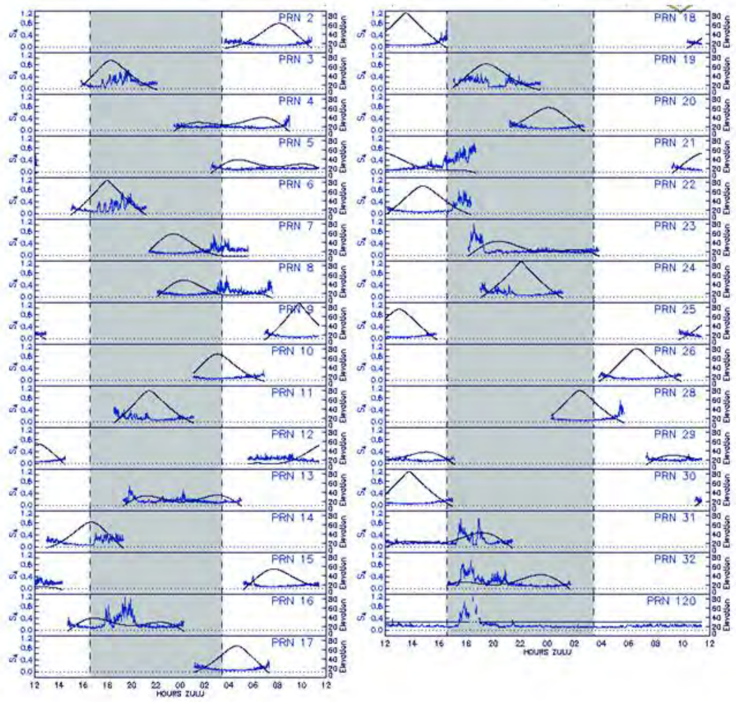


Figure 4. TEC and scintillations (S4 index) measurements with Depletions identified at station Alta Floresta, Brazil.

Nairobi – 22-23 Sept 2011 (GPS S4 and Elevation Angle)



Nairobi – 24-25 Sept 2011 (GPS S4 and Elevation Angle)

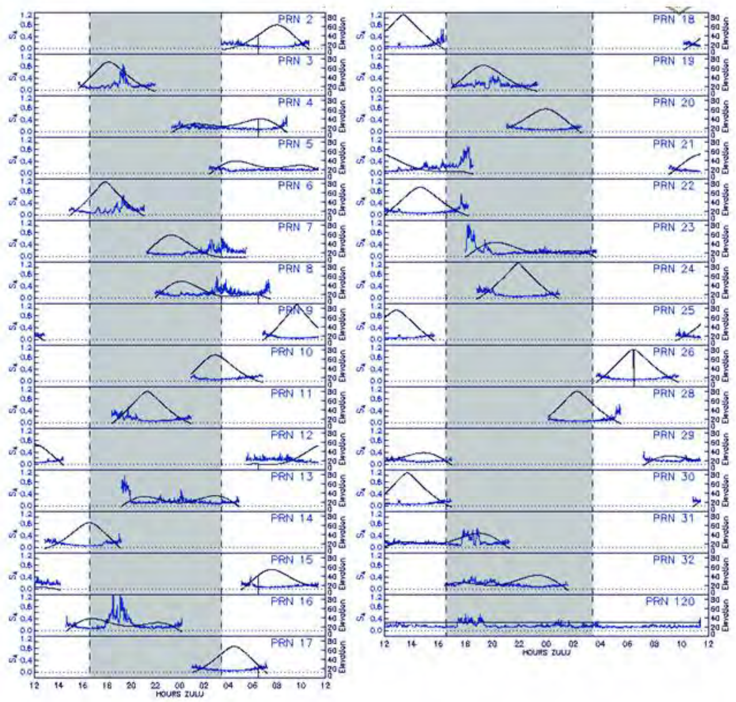


Figure 5. S4 scintillation index observed at Nairobi, Kenya, from 22 to 25 September 2011.

Distribution A: Approved for public release; distribution is unlimited.

The results of the work are in good agreement with previous studies done mostly in other equatorial regions. In particular, post-sunset enhancements and decreases of vertical TEC and corresponding increase of its monthly standard deviation were observed mainly in equinoctial months as shown in figure 6 taken from the mentioned paper. This behavior has been observed by other authors (Alex et al., 1989; McClure, 1977; Dabas et al., 1998; Basu and Basu, 1985) and has been considered as a strong indicator of abrupt scintillation onset, bubbles and spread-F phenomenon.

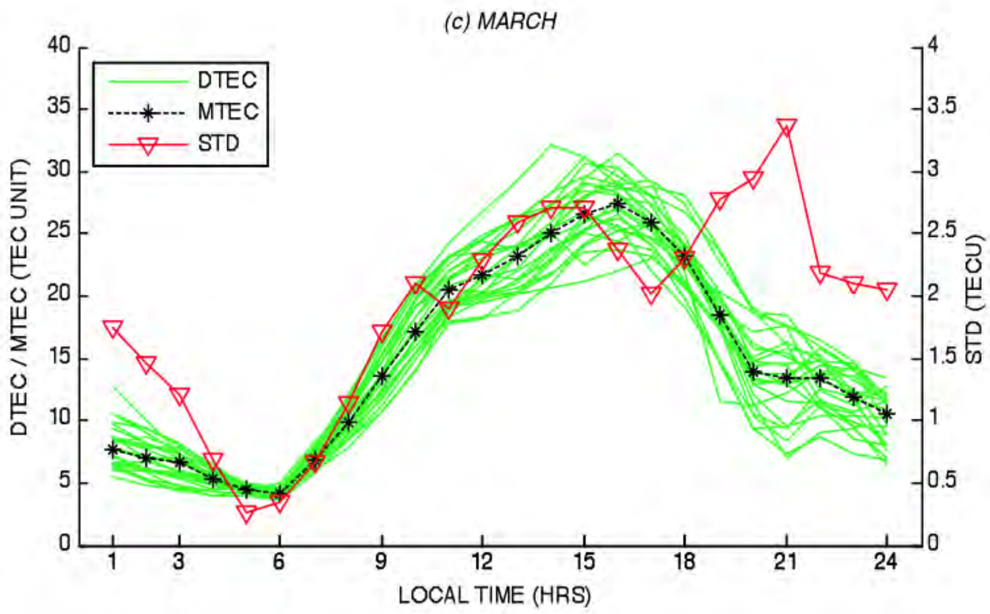


Figure 6: Diurnal (DTEC), standard deviation (STD) and monthly-median (MTEC) variation of VTEC for Ilorin, March 2009.

REGIONAL IONOSPHERIC SPECIFICATION

Considering that an important output of enhanced research activities in Africa would be finally the ability to now-cast ionospheric conditions over the continent, data ingestion in models techniques developed at the ICTP (Nava et al, 2006 and Nava et al, 2011) has been applied using low latitude African data. In particular, the ability to reproduce TEC data measured in locations distant from the one used to ingest data into the model has been tested as a way to check the possibility of producing realistic specification of the ionosphere. This objective is particularly challenging for a region like the equatorial one where ionospheric variability is very high.

The work done with Melessew Negussie, PhD student of Bahir Dar University in Bahir Dar, Ethiopia, for the equatorial sub-region of Ethiopia indicates that the techniques used are very promising. A paper with the results of this work will be sent shortly to Annales Geophysicae (“GPS sTEC ingestion to NeQuick 2 for East-African equatorial region ionosphere”, M. Nigussie, S.M. Radicella, B. Damtie1, B. Nava, E. Yizengaw, L. Ciraolo)

Data from a series of GPS receivers in the region of interest have been used. Table 3 show the coordinates of the locations involved in the study. Nazret station data were ingested into the NeQuick 2 electron density model developed at the ICTP in collaboration with the University of Graz, Austria (Rdicella and Leitinger, 2001 and Nava et al, 2008). Data from the other stations were used to test the ability of the model adapted with the Nazret data to specify the electron density distribution over the sub-region. Table 4 shows the distances and azimuth of the test stations relative to Nazret. The results indicate that the ability to reproduce the experimental data of slant TEC increases notably when the model is adapted by data ingestion from one station in comparison with the case when the model was used in a standard way being driven only by the daily solar flux.

Table 3: Station location coordinates

Station	Code	Geographic (Lat. , Long.)	Magnetic (Lat., Long.)
Asab	ASAB	(13.06,42.65)	(4.91,114.34)
Bahir Dar	BDAR	(11.6, 37.36)	(2.67, 109.18)
Nazret	NAZR	(8.57, 39.29)	(-0.25, 111.01)
Robe	ROBE	(7.11, 40.07)	(-1.69, 111.82)
Arba Minch Unv	ARMI	(6.06, 37.56)	(-3.03, 109.29)

Table 4: Distance and azimuth of test stations relative to Nazret

Station	Distance (km)	Azimuth (Deg.)
NAZR-ASAB	619.5	36
NAZR- BDAR	397.6	328.1
NAZR-ROBE	181.6	153.3
NAZR-ARMI	338	214.5

Figure 7, taken from the paper to be sent for publication, gives an example of the results obtained when slant TEC data for one full month (April 2007) are used. In numerical terms, Table 5 shows the monthly average of the mis-modeling values in TEC units obtained with the NeQuick 2 model before and after data ingestion for the four test stations.

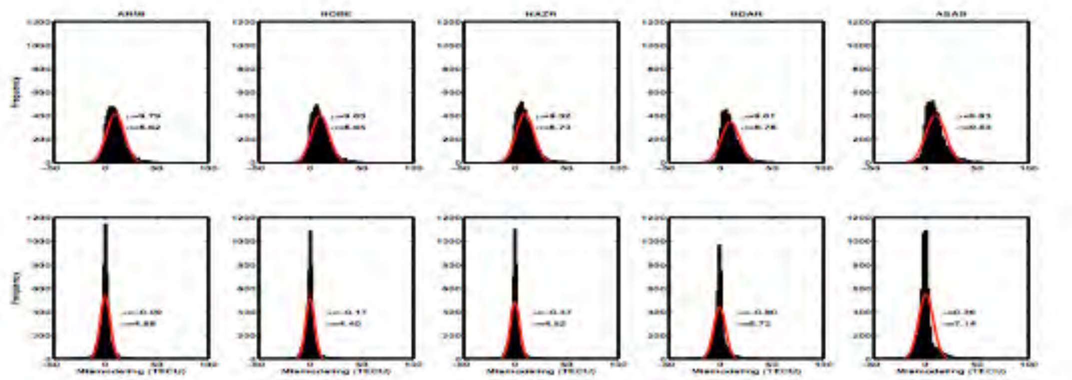


Figure 7: Distribution of the mismodeling before (top panels) and after (bottom panels) ingestion during April 2007.

Table 5: Mis-modeling values before and after Nazret data ingestion

Station	Mis-modeling Before ing. TEC units	Mis-modeling After ing. TEC units
Asab	9.83	0.36
Bahir Dar	9.61	-0.8
Robe	9.63	-0.17
Arba Minch Unv	9.79	-0.09

The good results obtained in this work indicate that adapting NeQuick 2 to one station data a realistic sub-regional ionospheric specification of the East-African ionosphere that lies in the trough area of the equatorial anomaly of the ionosphere can be obtained.

REFERENCES

Alex S, Koparkar, P.V and Rastogi, R.G., (1989). Spread-F and ionization anomaly belt, J. Atmos. Terr. Phys. (UK), 51, 371.

Basu, S. and Basu, S., (1985). Equatorial scintillations: advances since ISEA-6, J. Atmos. Solar Terr. Phys., 47, 753–768.

Dabas, R.S., Lakshmi, D.R., Reddy, B.M., (1998). Day-to-day variability in the occurrence of equatorial and low latitude scintillations in the Indian zone. Radio Science 33, 89–96.

Gentile, L.C. Burke, W.J. and Rich, F.J. (2006) A global climatology for equatorial plasma bubbles in the topside ionosphere, Ann. Geophys., 24, 163, 2006.

McClure, J.P., Hanson, W.B., Hoffman, J.H., (1977). Plasma bubbles and irregularities in the equatorial ionosphere. Journal of Geophysical Research 82 (19), 2650–2656.

Nava, B., Radicella, S. M.,Leitinger, R. and Coïsson, P. (2006), A near-real- time model-assisted ionosphere electron density retrieval method, Radio Sci., 41, RS6S16, doi:10.1029/2005RS003386.

Nava, B, Coïsson, P and Radicella, S.M. (2008), A new version of the NeQuick ionosphere electron density model, Journal of Atmospheric and Solar-Terrestrial Physics , doi:10.1016/j.jastp.2008.01.015

Nava, B., S. M. Radicella, and F. Azpilicueta (2011), Data ingestion into NeQuick 2, Radio Sci., 46, RS0D17, doi:10.1029/2010RS004635.

Radicella, S. M. and Leitinger, R. (2001), The evolution of the DGR approach to model electron densityprofiles, Adv. Space Res., Vol. 27, Issue 1, Pages 35-40

Valladares, C. and Doherty, P.H. (2009) The Low-Latitude Ionosphere Sensor Network (LISN), Proceedings of the 2009 International Technical Meeting of The Institute of Navigation